γ-RAY BURSTS AND NEUTRON STAR MERGERS*†

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Abstract

γ-ray bursts have baffled theorists ever since their accidental discovery at the sixties. We suggest that these bursts originate in merger of neutron star binaries, taking place at cosmological distances. These mergers release $\approx 10^{54} ergs$, in what are possibly the strongest explosions in the Universe. If even a small fraction of this energy is channeled to an electromagnetic signal it will be detected as a grbs. We examine the virtues and limitations of this model and compare it with the recent Compton γ-ray observatory results. We also discuss the potential application of grbs to study cosmology and show that these burst might lead to a new and independent determination of both H_0 and Ω.

I. PROLOGUE: γ-RAY BURSTS CIRCA 1973

γ-ray bursts (grbs) were accidentally discovered ahead of their time. Had it not been for the need to verify the outer space treaty of 1967 (which forbade nuclear experiments in space) we would not have known about these bursts until well into the next century. No one would have proposed a satellite to look for such bursts, and had such a proposal been

*Supported by a BRF grant.

†To appear in the Proceedings of the Lanczos Centenary: Editted by Moody Chu, Robert Plemmons, David Brown, and Donald Ellison, SIAM publications.

made it would have surely turned down as too speculative. The VELA satellites with omni-directional detectors sensitive to γ-ray pulses, which would have been emitted by a nuclear explosion, were launched in the mid sixties to verify the outer space treaty. These satellites never detected any nuclear explosion. However, as soon as the first satellite was launched it begun to detect puzzling, perplexing and above all entirely unexpected bursts. The lag between the arrival time of the pulses to different satellites gave a directional information and indicated that the sources are outside the solar system. Still, the bursts were kept secret for several years, until Kelbsdal Strong and Olson described them in a seminal paper [1] in 1973.

II. FALSE CLUES?

The rapid fluctuation in the signal (less than 10ms) suggested a compact source, a neutron star or a black hole. Several other clues focused the attention of theorists towards neutron stars at the disk of the galaxy.

First, came an analytic estimate [2] of the optical depth to $\gamma\gamma \rightarrow e^+e^-$. For an impulsive source we have: $\tau_{\gamma\gamma} \approx \sigma_T F D^2/R^2 m_e c^2$ where F is the fluence ($\approx 10^{-5} ergs/cm^2$ in the early detectors and $\approx 10^{-7} ergs/cm^2$ in Compton-GRO), D is the distance to the source and R its size (expected to be less than 10^9 from timing arguments). Since $\tau_{\gamma\gamma} > 1$ for $D > 100pc$, it was argued that the sources must be at the disk of the galaxy. Otherwise, it was argued an optical thick system will cool down and radiate its energy in the x-ray uv or optical band and not as γ-rays. The non-thermal spectrum also indicated that the sources are optically thin. Incidentally,, it was the confrontation between this argument and the indications from Compton-GRO that grbs are cosmological (which we discuss later) that have lead to claims that grbs require "new physics". We will see that it ain't necessarily so.

A very strong and long (1000 sec) burst was observed on March 5th 1979. The position of the burst coincided with a SNR remnant in the LMC supporting the idea that grbs originates on neutron stars.

Another clue came from the observation of absorption lines [3,4]. The lines were interpreted as cyclotron lines in a 10^{12}G magnetic field, a field strength that is found only on neutron stars.

These clues and others have led to the consensus that grbs arise on neutron stars in the disk of the galaxy [5], possibly in their magnetosphere.

III. BURSTS DISTRIBUTION CIRCA 1991

There were, however some indications that the sources might not be galactic. In 1975 Usov and Chibisov [6] suggested to use a logN-LogS test to check if the bursts have a cosmological origin. Later, in 1983 van den Bergh [7] analyzed the distribution of the 46 bursts that were known at that time and from the isotropy of this distribution he concluded that the sources are either local at distances of less than half of the galactic disk scale height or cosmological at redshift $z > 0.1$ (See also [8]). The cosmological solution was accepted with skepticism since with typical fluencies of $10^{-5} ergs/cm^2$ the bursts require $10^{49} ergs$ if they originate at distances larger than $100 Mpc$! In 1986 Paczyński [9] argued that the bursts are cosmological and suggested that some of the burst are lensed by intervening galaxies and that this will provide an observational test to the cosmological hypothesis. In 1989 Eichler, Livio, Piran and Schramm [10] (see also [11]) suggested that the bursts originate in neutron star mergers at cosmological distances (The possibility that grbs might be produced in neutron star mergers was also mentioned without specifying a model by [12,9,13,14]). However, in 1991, just before the Compton-GRO results were announced, Atteia *etal.* [15] reported (at a 3σ level) that the 244 bursts observed by the spacecrafts Venera 13, 14 and Phebus are concentrated towards the galactic plane, suggesting a disk population after all.

IV. NEUTRON STAR BINARIES

Another seemingly unrelated and unexpected discovery was make in 1975 by Hulse and Taylor [16] who found a pulsar, PSR 1913+16, that was orbiting around another neutron star. No one has predicted that such systems exist, but in retrospect it was not surprising. More than half of the stars are in binary systems. If some of these binaries survive the two core collapses (and the supernovae explosions) needed to produce the neutron stars they will end in a binary pulsar.

The binary pulsar have proven to be an excellent laboratory for testing General Relativity. The binary system emits gravitational radiation which is too week to be detected directly, but its back reaction could be observed. By carefully following the arrival time of the pulsar's signals Taylor and his collaborator have measured the pulsar's orbit. They have shown that the binary spirals in just in the right rate to compensate for the energy loss by gravitational radiation emission (with two neutron stars, tidal interactions and other energy losses are negligible). For PSR 1913+16 the spiraling in takes place on a time scale of $\tau_{GR} = 3 \times 10^8$years, in excellent agreement with the general relativistic prediction [17]. These observations not only confirm the general relativistic prediction, they also assure us that the orbit of the binary is indeed decreasing and that inevitably in 3×10^8 years the two neutron stars will collide and merge!

V. SOURCE COUNT AND EVENT RATE

For many years only one binary pulsar was known. A simple estimate based on the observation of one binary pulsar in several hundred observed pulsars led Clark *etal.* [18] to conclude that about 1 in 300 pulsars is in a binary. With a pulsars' birth rate of one in fifty years this led to a binary birth rate of one in 10^4 years. Assuming a steady state, this is also the merger rate. This estimate ignored, however, selection effects in the detection of binary pulsars vs. regular ones. Specifically PSR1913+16 is an extremely bright pulsar

which is detectable from much larger distance than an average pulsar. Currently there are four known binary pulsars and an analysis based on their luminosities and life times [19,20] suggests that there are $\sim 10^4 - 10^5$ neutron star binaries in the galaxy and that their merger rate is one per 10^6years per galaxy. This corresponds to ~ 100 mergers per year in galaxies out to a distance of 1 Gpc and about 10^3 per year to the horizon. Narayan, Piran and Shemi [19] also predict that a similar or somewhat smaller population of neutron-star black hole binaries will exist.

VI. NEUTRON STAR MERGERS

It was immediately realized, after the discovery of PSR1913+16 that the binary produces a unique chirping gravitational radiation signal during the last seconds before the neutron stars merge. These signals are probably the best candidates for detection of gravitational radiation. However, these events are rare and to observe them (gravitationally) in our life time we must turn to extragalactic events. This is the aim of the advanced gravitational radiation detectors like LIGO [21].

As the strongest sources of gravitational radiation neutron star mergers attracted the attention of relativists, but most astronomers ignored them as being too rare to be of interest. Clark and Eardley [22] have shown that the binding energy released in a neutron star binary merger is $\sim 5 \times 10^{53} - 10^{54} ergs$, making these events possibly the most powerful explosions in the Universe. A significant fraction of this energy is emitted as gravitational radiation, both prior and during the collision. A very sophisticated gravitational radiation detector, LIGO, is built to detect these gravitational radiation signals. But it will be around the turn of the century when it is operational.

As the neutron stars collide a shock forms and the stars heat up. Most of the binding energy is emitted as neutrinos [22]. The neutrino burst is comparable or slightly stronger than a supernova neutrino burst (such as the one detected by Kamiokande and IMB from 1987A). To detect extragalactic events at cosmological distances we need a detector which

is $\approx 10^8$ times larger than those detectors. With regular supernova neutrino bursts being a hundred times more frequent it is clear that these neutrino signals are not the prime candidates for detection.

Neutron star mergers are hiding from us by emitting their energy in two channels with extremely small cross sections. If even a small fraction of the energy is channeled to an electromagnetic signal, its much large cross section will make it much easier to observe. For many years, I kept wondering what are the possible observational consequences of such events [11].

VII. ENERGY CONVERSION

Goodman, Dar and Nussinov [14] suggested that the neutrino-anti neutrino annihilation $\nu + \bar{\nu} \rightarrow e^+ + e^-$ converts a small fraction of the neutrino supernova burst to electron-positron pairs which in turn annihilate to γ-rays, heat the surrounding envelop and provide the energy required to power the supernova shock wave. In 1989, Eichler, Livio, Piran and Schramm [10] (see also [11]) suggested that the same mechanism operates in neutron star mergers and converts $\sim 10^{-3}$ of the emitted energy to pairs and γ-rays. This corresponds to $10^{51} ergs$, roughly sufficient for detection of the bursts from cosmological distances. Eichler *etal.* [10] used the old estimate of Clark *etal.* [18] for the merger rate and suggested that these events would be detected by Compton observatory as grbs.

More recently, alternative energy generation mechanism such as magnetic field recombination [23] or accretion onto the neutron star [24] have been proposed and it was argued that they provide comparable amounts of energy.

VIII. FIREBALLS AND RELATIVISTIC EFFECTS

A. Why Fireballs

One of the most robust results in the theory of grbs is that any burst which is at a cosmological distance must inevitably form a “fireball”. If grbs are indeed cosmological they are initially optically thick, as Schmidt [2] have argued. How can there be a γ-ray burst from such a source? Goodman [13] considered a dense sphere of γ-ray photons and pairs, which he called a “fireball”. He has shown that a cosmological grb source will quickly form an extremely optically thick soup of electrons, positrons, and photons, plus any baryons which may have been injected initially. This optically thick relativistic fluid is referred to as a fireball. The immense pressure in a fireball causes the fluid to expand relativistically to a very large radius before the radiation can finally escape. The fireball will expand and cool, just like the early Universe (unlike our Universe the gravitational force is unimportant). As the fireball cools its temperature drops with $T \propto 1/R$ until the electron positions annihilate (the annihilation is complete at $T \approx 20$ keV) and the radiation escapes. The radiation fluid has reached in the meantime a relativistic velocity relative to an observer at infinity and its Lorentz factor $\Gamma \approx R_{esc}/R_0 \approx T_0/T_{esc} \approx 10^3 - 10^4$. The escaping photons, which have a typical energy of 20 keV in the local frame are blue shifted relative to an observer at infinity and their observed energy is $\epsilon_{obs} \approx \Gamma T_{esc} \approx T_0$, of the same order as the initial energy. In this way the optical depth argument which limited the distances to the sources is bypassed and there is no need to introduce “new physics” to explain grbs from cosmological distances.

Paczyński [9] have shown that similar effects take place if the radiation is released in a quasi-stationary manner. In this case the radiation flows out as a relativistic wind, with $T \propto 1/R$ and $\Gamma \propto R$. The radiation ceases to behave like a fluid and escapes when $T \approx 20$ keV in the local frame. The escaping x-ray photons are blueshifted to much higher energies in the observer frame.

B. Do Fireballs Work?

The fireball model faces two serious objections: the origin of the observed nonthermal spectrum and the effects of baryons.

There is no simple way to explain the non-thermal spectrum from a fireball that passes an optically thick phase and termalizes. It is possible that different regions in a realistic, inhomogeneous fireball move with significantly different Lorentz Γ factors and that the observed spectrum is a blending of thermal spectra to a non thermal one. Simple calculations of the spectrum of a spherical fireball [25] show some deviation from a thermal spectrum, but it is not large enough. Alternatively one could hope that the spectrum would become nonthermal in the transition from optically thick to optically thin regimes. However, this transition takes place at ≈ 20keV in the local frame. The energy injected from annihilation at this stage is insignificant and the temperature is too low for inverse Compton scattering to be effective. It seems that there is no clear mechanism that will modify the photons' black body spectrum in this stage.

One expects that some baryons will be injected into the fireball. Shemi and Piran [26] have shown that the baryons have two effects. For $10^{-11} M_\odot < M < 10^{-8} M_\odot (E_0/10^{51} ergs)$ the baryons dominate the opacity (long after all the pairs have annihilated) without influencing the fireball's inertia. The fireball continues to be optically thick until $\tau_g = \sigma_T M/R^2 = 1$. This leads to a longer acceleration phase and to a larger final Lorentz factor $\Gamma_f \approx R/R_0 \approx T_0/T$. However, the final energy of the escaping radiation remains unchanged with $\epsilon \approx \Gamma T \approx T_0$.

Larger baryonic load changes the dynamics of the fireball. As the fireball expands $\rho \propto R^{-3}$ while $e \propto r^{-4}$. If $M > 10^{-8} M_\odot (E_0/10^{51} ergs)$ the baryonic rest mass will dominate the energy density and the fireball's inertia before the fireball becomes optically thin. In these cases all the energy will be used to accelerate the baryons with $E_K = Mc^2\Gamma \approx (E_0 + Mc^2)/(E_0 T/Mc^2 T_0 + 1)$. The final outcome of a loaded fireball will be relativistic expanding baryons with $\Gamma \approx E_0/Mc^2$ and no radiation at all.

Several ideas have been proposed to avoid the baryonic load problem. These include: (i) Separation of the radiation and the baryons due to deviations from spherical symmetry - the radiation escaping along the axis and the baryons being ejected preferably in the equatorial plane [27,28] and (ii) generation of a radiation fireball with very small amounts of matter via magnetic processes [23].

C. Energy Conversion, Once More

If the baryonic contamination is in the range $10^{-5}E_0 < Mc^2 < 0.1E_0$ all the initial fireball energy will be converted to extremely relativistic protons moving at a Lorentz factors $10 < \Gamma \approx E_0/Mc^2 < 10^5$. Mészáros, and Rees [29–31] (see also earlier work by Blandford and McKee [32,33] and more recent work by Katz [34,35] Mészáros, Laguna and Rees [36], Piran [37] and Shemi [38]) suggested that this energy could be converted back to γ-rays when this baryons interact with the surrounding interstellar matter. A shock, quite similar to a SNR shock, forms and it cools predominantly via synchrotron emission in the x-rays. The x-ray photons will be blueshifted to γ-rays in the observer frame due to the relativistic velocity of the fireball. The relativistic motion will also lead to a short time scale for the burst. Alternatively, the accelerated baryons could interact with a pre-merger wind that surrounds the fireball [23]. In both cases the interaction with the surrounding material will lead once more to the conversion of the energy: from kinetic energy back to radiation. Since this phase is taking place in an optically thin region the photons will not thermalize and the emerging spectra will be non thermal, as observed. Thus, this process seems to resolve at one stroke both major objections to the fireball scenario.

IX. RELATIVISTIC BULK MOTION - AN ALTERNATIVE?

Several years ago Krolik and Pier [39] noticed that the large optical depth problem, raised by Schmidt [2] could be avoided if the source is moving towards us at a relativistic velocity. Several effects combine to remove this constraint. First the emission is beamed

with $\theta \approx 1/\Gamma$ the anisotropy of the emission lowers the required density of photons at the source. More important is the fact that the observed photons have been blue shifted. What is observed as γ-rays on earth is in fact x-rays or even uv photons at the source. At the source only a minute fraction of the photons is energetic enough to produce pairs and the optical depth problem to $\gamma\gamma \rightarrow e^+e^-$ disappears. Krolik and Pier have obtained an estimate for the minimal bulk motion required to explain the observed bursts which, depending on the location of the bursts, leads to Γ of hundreds or more.

A fireball is, in some sense, a variant of the Krolik and Pier idea. Here we also observe blue shifted photons emitted in a rest frame that is moving relativistically towards us. However, the relativistic velocity of the fireball is not due to a bulk motion of the source but to relativistic expansion, which is an inevitable part of the fireball scenario and follows from the dynamics of the model. Since the expansion is isotropic (at least in a spherical fireball) the radiation is emitted isotropically. On the contrary, a moving source beams its radiation in the direction of its bulk motion.

Kinematics attempts to explain grbs on the basis of bulk motion are generally misleading since they ignore the huge energy required to produce a relativistic bulk motion of any macroscopic source. First it is hard to reconcile the required high Γ with the fact that the highest observed relativistic motion in any other astronomical system is less than ten and even this motions appears extremely rarely in some AGNs' jets. Moreover, The kinetic energy required, for example, for a stellar mass source with a "modest" Γ of 100 is 10^{56}ergs. It seems that any model that is based on an ad hoc relativistic bulk motion of the source creates a severe problem - how is the source accelerated which is as problematic as the phenomenon that it attempts to explain.

X. γ-RAY BURSTS DISTRIBUTION CIRCA 1992

The Compton γ-ray observatory was launched in the spring of 1991 (see [40] for a review). It includes an omni-directional γ-ray burst detector (BATSE) which, with a limiting

sensitivity of $\approx 10^{-7} ergs/cm^2$, is the most sensitive detector of this kind flown. By the summer of 1992 BATSE has detected more than 400 bursts, more than all previous detectors combined. BATSE is also capable of obtaining a directional information on the bursts on its own. Within four month from its launch BATSE has collected enough data to conclude that the distribution of grbs sources is isotropic [41]. The average V/V_{max} of the source is $\approx .33$ many σ from the value 0.5 of a population distributed homogeneously in flat space [41]. This show that the sources are not distributed homogeneously in an Eucleadian space. They are either concentrated towards us or alternatively they are distributed homogeneously in a curved space-time and the observed inhomogeneity results from this curvature.

These observations rule out all local galactic disk models. A possibility that was accepted by a small minority at first and gained more and more support latter. The observations are consistent with three possible populations: (i) Cosmological population (ii) Galactic halo population with a large core radius ($> 50 kpc$) and (iii) A population, such as comets at the Oort cloud, centered around the solar system. We will turn to the second and third possibilities, before summing up the status of the cosmological model.

A. Galactic Halo Models

Galactic Halo models require a halo population with a large core radius (to avoid an anisotropic enhancement towards the galactic center). This is a new population of astronomical objects, which was not seen elsewhere [24]. By now there have been several suggestions how to form a neutron population of this kind. These include either ejection from the galactic disk or formation in site. However, the typical distances of a galactic halo object, lead to several difficulties which make such a location quite unfavorable for production of grbs.

Approximately $10^{41} ergs$ are needed for bursts at the halo, quite a large amount for a neutron star. With a typical size of $10^6 cm$ the optical thickness for $\gamma\gamma \rightarrow e^+e^-$ is $\approx 10^8$. The energy requirement and the optical depth mean that the low energy, optically thin

neutron star models suggested for galactic disk sources are inapplicable to grbs at the halo. Furthermore, galactic halo sources inevitably involve an opaque pair plasma fireball, just like cosmological sources [42]. These fireballs reach, however, lower relativistic Lorentz factors before becoming optically thin or matter dominated. Those relatively moderate Lorentz factors are unlikely to suffice for producing grbs.

B. Local Population

Typical objects in the solar system have a very small binding energy per baryon and it is difficult to imagine a mechanism in which such objects generate energies in the γ-ray range (see however [43]). The only hope is probably via a magnetic phenomenon. Solar flares do generate grbs which are detected by Compton-GRO (these are identified by their location and spectrum [44]). However, comparison of the size and masses involved in these events make it inconceivable that similar conditions can be achieved elsewhere in the vicinity of the solar system, without leaving any other trace.

C. Cosmological Population

Several groups [45–48] have shown that a cosmological population is compatible with the observed V/V_{max} distribution. The apparent concentration towards us is an artifact of a combination of redshift effects and a possible cosmological evolution. Depending of the cosmological model and the source evolution we have $0.3 < Z_{av} < 3$. For $\Omega = 1$ and no evolution $Z_{av} \approx 1$ [46].

The cosmological model has a clear prediction [46,49,50]: a positive correlation between the faintness of a burst (correlated with distance) and redshift signatures through the burst duration and spectrum. This correlation could be masked by large intrinsic variations among bursts, but should eventually be observed when enough data accumulate.

The event rate needed to explain the observation is in an amazing agreement with the rates estimated for neutron star mergers [19,20]. Because of a historical coincidence the

forth binary pulsar, PSR1534+12, which played a decisive role in the determination of the merger rate [19,20], was discovered [51] a few month before Compton-GRO was launched and the prediction of the neutron star merger rate were not influenced by the rates required to explain the Compton-GRO results.

Several other cosmological models were suggested after Compton-GRO [52–55]. Within the cosmological framework, the neutron star merger scenario is the most conservative one possible. It is the only one based on a source population that definitely exists. We know its members will merge, we can be certain that huge quantities of energy will be released in such mergers, and we find the merger rate to be comparable to the observed burst rate.

XI. γ-RAY BURSTS DISTRIBUTION CIRCA 1994

BATSE on Compton-GRO has detected so far more than 700 grbs [56]. With more data and better statistics the grb distribution looks more isotropic than ever. $\langle V/V_{max}\rangle$ converges to a value of 0.31 demonstrating, if it was ever necessary, that the preliminary value was not a statistical fluctuation. While only 5% of the researcher present in the first γ-ray bursts Huntsville conference in Oct 1991 supported the cosmological hypothesis more than 50% of those present in the second meeting in Oct 1993 were in its favor. In two year the binary neutron star merger model have gone the whole way from a crazy idea supported by a few enthusiasts to become *the most conservative current model* [57].

The improved data poses more and more problems to the Galactic Halo model as it pushed the typical distance to a galactic halo source (to be compatible with isotropy) farther and farther away. The current data requires a core radius $\gtrsim$80kpc [58] which, as predicted in 1992 [50], is incompatible with the distribution of the dark halo of the Galaxy (the latter being more concentrated towards the galactic center).

Recently Norris *etal.* [59] have found the predicted [46,49,50] correlation between the intensity and the duration of the bursts and between the intensity and their hardness ratio. This correlation is a clear indication of a cosmological origin. It also provides an independent

measure of the typical red shift to a grb. The analysis suggests that the bursts originate from a population with $Z_{max} \approx 1$, in agreement with analysis of the distribution of intensity of the bursts!

It seems that the data support the cosmological hypothesis. However, there are still claims that not everything is settled yet. Quashnock and Lamb [60,61] pointed out that there is a nearest neighbors excess in the first BATSE catalogue, which they interpret as an indication that grbs repeat. Clearly repetition of bursts from the same location rules out the neutron star merger model. The huge energy budget required will make it quite difficult to construct any cosmological repeating source (note that a cosmological source releasing several bursts of $\approx 10^{51}$ergs per year has an average energy output of $\approx 10^{44}$ergs/sec which equals the luminosity of a qso!). In a different paper Quashnock and Lamb [62,63] show that if one divide the bursts to sub populations according to their strength than one discovers that those sub-populations are anisotropic. The combination of the two effects, suggests, according to Quashnock and Lamb, that the bursts do originate at the galactic disk.

Several problems with the repeater hypothesis caused, however, some doubt. Narayan and Piran [64,65] have shown that there is an equal excess of furthers neighbors (that is bursts at the antipodal location of other bursts). Such an excess cannot be explained by any physical model and its existence suggests that both phenomena arise from some inexplicable observational effect. Additionally, there is some internal inconsistency between the narrow peak of the nearest neighbors ($\approx 5^o$) and the typical positional errors of the bursts which were much larger (the positional error depended on the strength of the bursts and for weak bursts it could reach up to 20^o) (see also [66]). Preliminary studies of the full BATSE catalog (containing more than 700 bursts) [56] show no nearest or farthest neighbor excess and no anisotropy of sub populations. Hence the repeater hypothesis and the sub population anisotropy are probably ruled out (see however [61,63]) and with this disappears the last evidence in favor of a galactic disk origin.

XII. CLUES REVISITED

Before concluding we turn once more to the clues discussed earlier. The optical depth problem disappeared in some sense and remained in another. Relativistic effects, due to the expansion of the fireball [13,9], were not taken into account in the original argument [2] which is flawed. The resulting spectrum from the expanding fireball has the right energy range but to a first approximation it is thermal. It is a non-trivial (but not impossible) task to obtain a nonthermal spectrum. This problem is shared by all cosmological and galactic halo models.

The March 5th event was one of three soft γ-ray repeaters, which have a softer spectrum and produce repeated bursts from the same source, unlike all other sources [5]. It is by now generally accepted that these are most likely a different phenomenon.

The nature of the cyclotron lines has been fairly controversial since they were first reported [67,68]. Mazets *etal.* [3] claimed that single "cyclotron absorption lines" were present in 20 bursts, with a broad distribution of line energies (27–70 keV), but with only five lines having energies under 50 keV. This is in conflict with the GINGA experiment which discovered three systems of lines, all with nearly identical energies, all under 50 keV [4]. So far, no lines have been detected with any experiment on the Compton Gamma Ray Observatory.

XIII. SOME OPEN QUESTIONS

It would be misleading to draw a picture in which the grb enigma has been completely solved. There are still some open questions within the context of the cosmological model, within the fireball model and within the more specific neutron star merger model.

The first puzzle might also be the best clue to the problem. Several groups [69–71] have shown that grbs can be divided to two populations of short (shorter than $\approx$ 1sec vs. long bursts (longer than $\approx$ 1sec) or equivalently variable vs. smooth. The number count (LogN-LogS) distributions of both sub populations agree with cosmological distributions. More

surprisingly the maximal peak luminosity of the bursts in both sub population is equal to within a factor of two even though the total energy released varies by more than a factor of ten [71]. This might be an accident but it is more likely a possible clue for a mechanism that controls the emission in the bursts, possible at the outer edge of a relativistic fireball. At present there is no explanation for that.

It is clear from the current understanding of fireballs that the question of whether or not a fireball will produce a grb, and what kind of a burst it produces, depends almost entirely on the ratio E_0/M. This is because the asymptotic Lorentz factor of the baryons is given by $\gamma \sim E_0/Mc^2$. Therefore, if E_0/M is too small, i.e. if the baryonic load is too large, the flow will not reach ultra relativistic velocities and there is unlikely to be a grb. The critical value seems to be $\Gamma \gtrsim 10^2$, which produces a rather strong limit on the amount of baryonic load namely $M \lesssim 10^{-5} M_\odot (E_0/10^{51}\mathrm{ergs})$. It is difficult to satisfy such a strict constraint. This leads to an important set of open questions namely: Even if M is larger than the above limit, can there still be isolated regions in a fireball where the local E/M ratio is much higher than average and can such regions produce the observed bursts? Can instabilities produce a phase separation between low and high E/M regions? Can the same instabilities also explain the extraordinary variety of burst profiles observed?

Within the neutron star merger model the baryonic load is a severe problem. However, the model also offers a simple solution. Mochkovich *etal.* [28] and Piran Narayan and Shemi [27] pointed out that due to the centrifugal force the matter forms a funnel along the rotation axis in binary neutron star merger. The baryonic load is much lower within the funnel and this is a natural regime in which E/M will be high. This suggestion has been confirmed by numerical simulations of neutron star mergers that were carried our recently by Davies *etal.* [72].

Davies *etal.* [72] find that the coalescence, from initial contact to the formation of an axially symmetric object, takes only a few orbital periods. Some of the material from the two neutron stars is shed, forming a thick disk around the central, coalesced object. The mass of this disk depends on the initial neutron star spins; higher spin rates resulting

in greater mass loss, and thus more massive disks. For spin rates that are most likely to be applicable to real systems, the central coalesced object has a mass of $2.4M_{\odot}$, which is tantalizingly close to the maximum mass allowed by any neutron star equation of state for an object that is supported in part by rotation. Using a realistic nuclear equation of state Davies *etal.* estimate the temperatures after the coalescence: the central object is at a temperature of $\sim$ 10MeV, whilst the disk is heated by shocks to a temperature of 2-4MeV. The disk is thick, almost toroidal; the material having expanded on heating through shocks. This disk surrounds a central object that is somewhat flattened due to its rapid rotation.

An almost empty centrifugal funnel forms around the rotating axis and there is practically no material above the polar caps. This funnel provides a region in which a baryon free radiation-electron-position plasma could form. Neutrinos and antineutrinos from the disk and form the polar caps would collide and annihilate preferentially in the funnel (the energy in the c.m. frame is larger when the colliding ν and $\bar{\nu}$ approach at obtuse angle, a condition that easily holds in the funnel). The numerical computations do not show any baryons in the funnels. The resolution of the computation is insufficient, however, to show that the baryonic load in the funnel is as low as needed. The neutrinos radiation pressure on polar cap baryons can generate a baryonic wind that will load the flow. Estimates of this effect [73,74] show that it is negligible if the temperature on the polar caps is sufficiently low. The estimated temperature from our computations is $\approx$ 2MeV, which is marginal. Our temperature estimate is, however, least certain in low temperature regions like this. The current simulations are clearly not accurate enough and do not include enough detailed physics to answer the question whether neutron star mergers could, indeed, produce the required conditions for the initial fireball.

The numerical calculations support earlier suggestions [27] that the energy release in a binary neutron star merger is anisotropic, the fireball appears as a jet along the rotation axis. This poses an immediate constraint on the model. If the width of the jet is θ than we observe grbs only from a fraction $2\theta^{-2}$ of binary neutron star mergers. The rates of grbs and binary neutron star mergers agree only if $\theta \gtrsim 0.2$ (unless the rate of binary neutron

star mergers is much higher than the current estimates). A condition which at first glance is satisfied by the funnel seen in the current numerical simulation. The beaming will also change of course the overall energy budget and lower the overall energy by a factor of $\approx \theta^2$.

XIV. γ-RAY BURSTS AS TOOLS TO EXAMINE COSMOLOGY

If they bursts are cosmological then we can employ them to explore cosmology, regardless of the nature of the sources. Thus, grbs could have much deeper and wider significance. If, as some preliminary tests indicate, grbs are indeed standard candles then they can be used directly in a count tests. Piran [46] addressed this problem for the first time in 1992, with a relatively poor set of data by comparing the average $\langle V/V_{max}\rangle$ to the one resulting from various theoretical cosmological distributions. Later Wickaramasinghe *etal.* [75] and Mao *etal.* [71] used the LogN-LogS test to obtain a more precise measure. Currently this estimates have been done using only the first BATSE catalogue. The fuller catalog that contains three times more bursts will naturally provide a better data set. In principle the test is similar to previous attempts to measure q_0 (and hence Ω) from galaxy counts or qso counts. In both cases the test failed when it was discovered that the observed objects show a significant density and luminosity evolution which screens the cosmological effects. Here, the LogN-LogS test can be improved slightly by combining it with the correlation test of Norris *etal.* [59] that provide an *independent* test of Z_{max} of the observed grb population. But history could repeat itself with the grb population and evolution could mask cosmological effect here as well [46].

An additional improvement, which in principle could yield a determination of Hubble's constant H_0, could take place towards the end of the century if and when grbs will be found to coincide with gravitational radiation emission from the merger. Shutz [76] pointed out that the gravitational radiation signal from a merger provides a direct measure of the distance to the source. The combination of the distance and redshift estimates would provide a new and independent way to measure H_0.

XV. EPILOGUE: γ-RAY BURSTS CIRCA 2000

At present there are no known optical counterparts to grbs. Since neutron star binaries might be ejected from dwarf galaxies, we predict [23], that grbs occur within a few tens of arcsecond from dwarf galaxies and within but not necessarily at the center of ellipticals. Optical identification of some parent galaxies, could support this model and the location of the burst relative to the galaxy could distinguish this model from other cosmological scenarios that involve supermassive black holes or other objects located in the centers of galaxies [52–54].

The scenario makes one unique prediction: strong γ-ray bursts should be accompanied by a gravitational wave signal [27,46,23] (though the reverse need not necessarily be true if the γ-rays are beamed). These signals should be detected by LIGO [21] when it becomes operational (hopefully by the year 2000). A coincidence between gravitational radiation signals from the final stages of the merger and grbs could prove or disprove this model. It could also serve to increase the sensitivity of the gravitational radiation detectors [77]. Hopefully, this coincidence will be detected and the model will be confirmed when gravitational radiation detectors will become operational at the turn of the century. LIGO should provide good distance estimates to individual bursts [76] and should also pinpoint the exact time of the merger. The distance measurement to the bursts could provide an additional cosmological information and in principle could lead to a new and independent measurement of Hubble's constant H_0. ,

I would like to thank Ramesh Narayan for many helpful discussions.

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